# Concrete Arch Dams

**Best Practices in Dam and Levee Safety Risk Analysis**

**Part E – Concrete Structures**

**Chapter E-4**

**Last modified June 2017, presented July 2018**

US Army Corps of Engineers®

# Outline

- Objectives
- Key Concepts
- Case History
- Normal and Flood Loading
- Seismic Loading

# Objectives

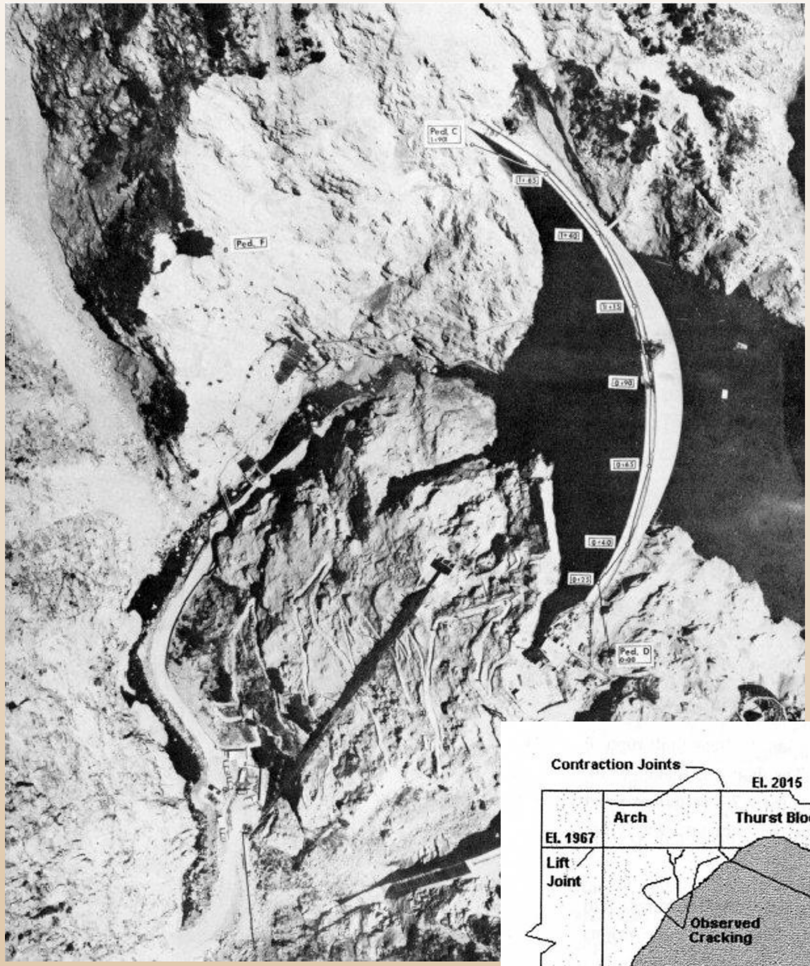
- Understand the mechanisms that affect arch dam failure
- Understand how to construct an event tree to represent arch dam failure
- Understand how to estimate event tree branch probabilities and probability of breach

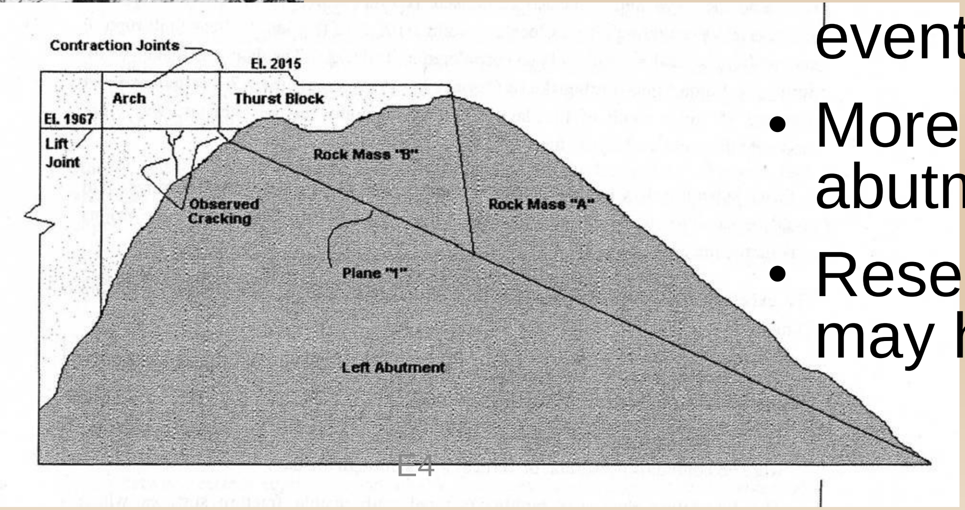
# Key Concepts

- Arch dams are forgiving structures – if one area is overstressed, load can be redistributed and transferred by arch action to the abutments
- Relies on load transfer to the abutments for stability
- Sliding on weak foundation discontinuities primary cause of historical arch dam failures (covered in another chapter)
- No known failures of arch dams due to structural distress or seismic loading
- Seismic potential failure modes typically most important from structural risk perspective
- Concrete properties are important (covered in another section)
- Estimating risks is difficult, relies primarily on traditional 3-D finite element analyses and judgmental probabilities
- Cracking does not equal failure

# Case History

# Pacoima Dam, CA





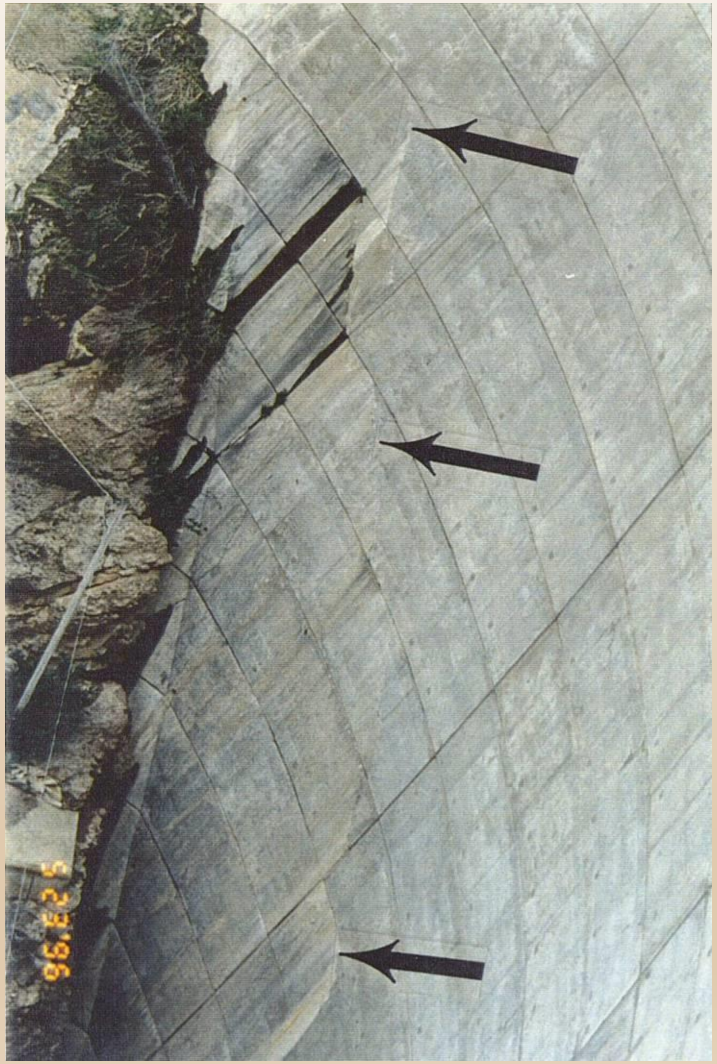

- 370' high flood control arch dam
- 1971 M6.6 San Fernando and 1994 M6.8 Northridge earthqukes
- Opening of joint between dam and left thrust block, cracking of thrust block, left abutment rock movements (both earthquakes, even with remediation after 1971 event)
- More movement of left abutment in 1994
- Reservoir was low, or dam may have failed

# Normal and Flood Loading

# Normal Operations

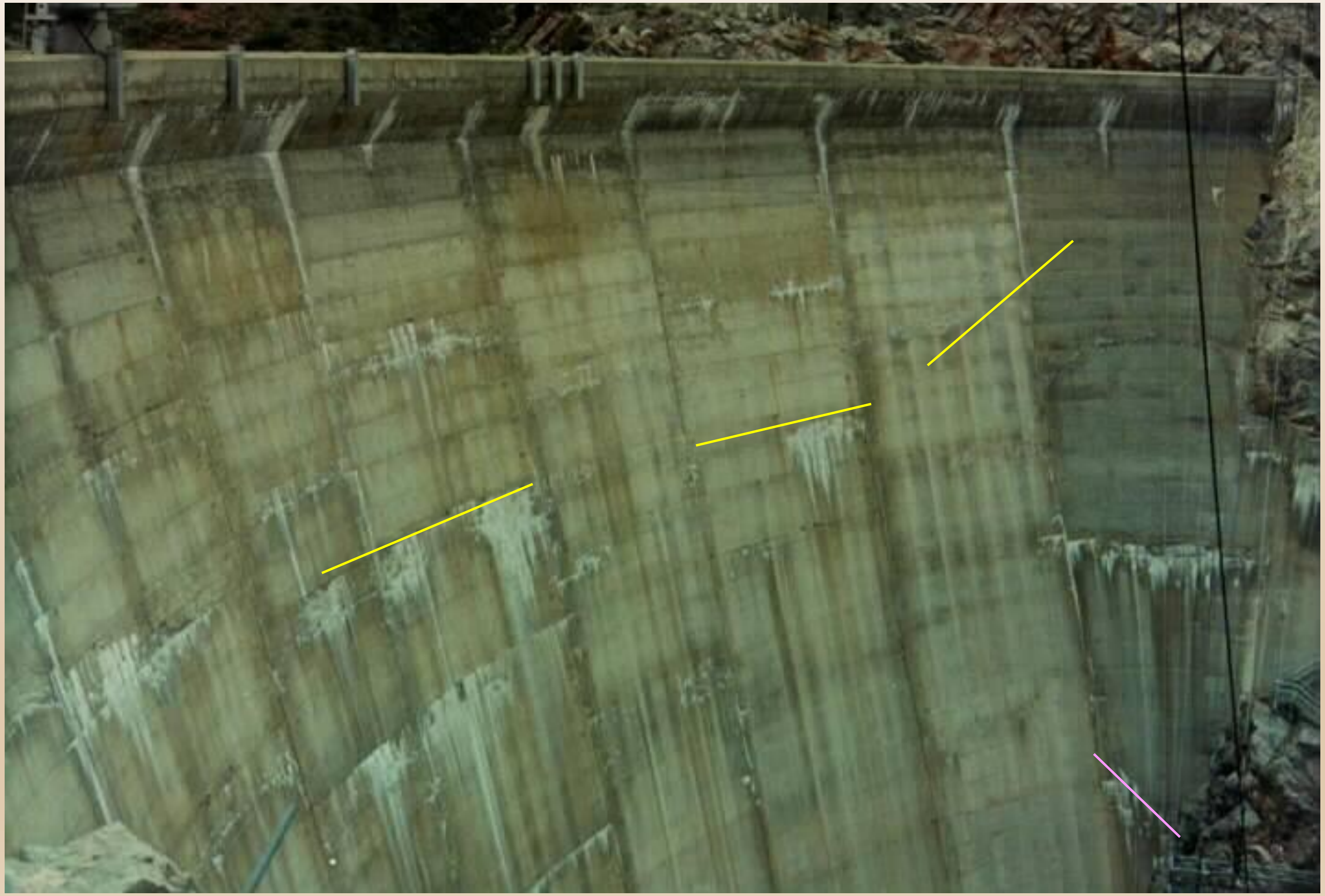
- If analyses indicate good behavior expected, no indications of problems or clear potential failure modes identified, may want to consider failure likelihood negligible
- If there is a well defined crack pattern or sequence that could lead to a potential failure mode, develop an event tree specific to that potential failure mode (covered in another chapter) and estimate branches based on analysis results

# Potentially Adverse Cracks




Cracks in thin arch dam from low reservoir and high temperature parallel to abutment.  Upstream movement caused moment and tension on downstream face.

# Cracking (ASR and Abutment Protrusion)



- Alkali Silica Reaction causes the concrete expand resulting in potentially adverse cracking patterns for an arch dam (yellow)
- Cracks at abutment protrusions are common but seldom problematic (pink)

# Flood Loading

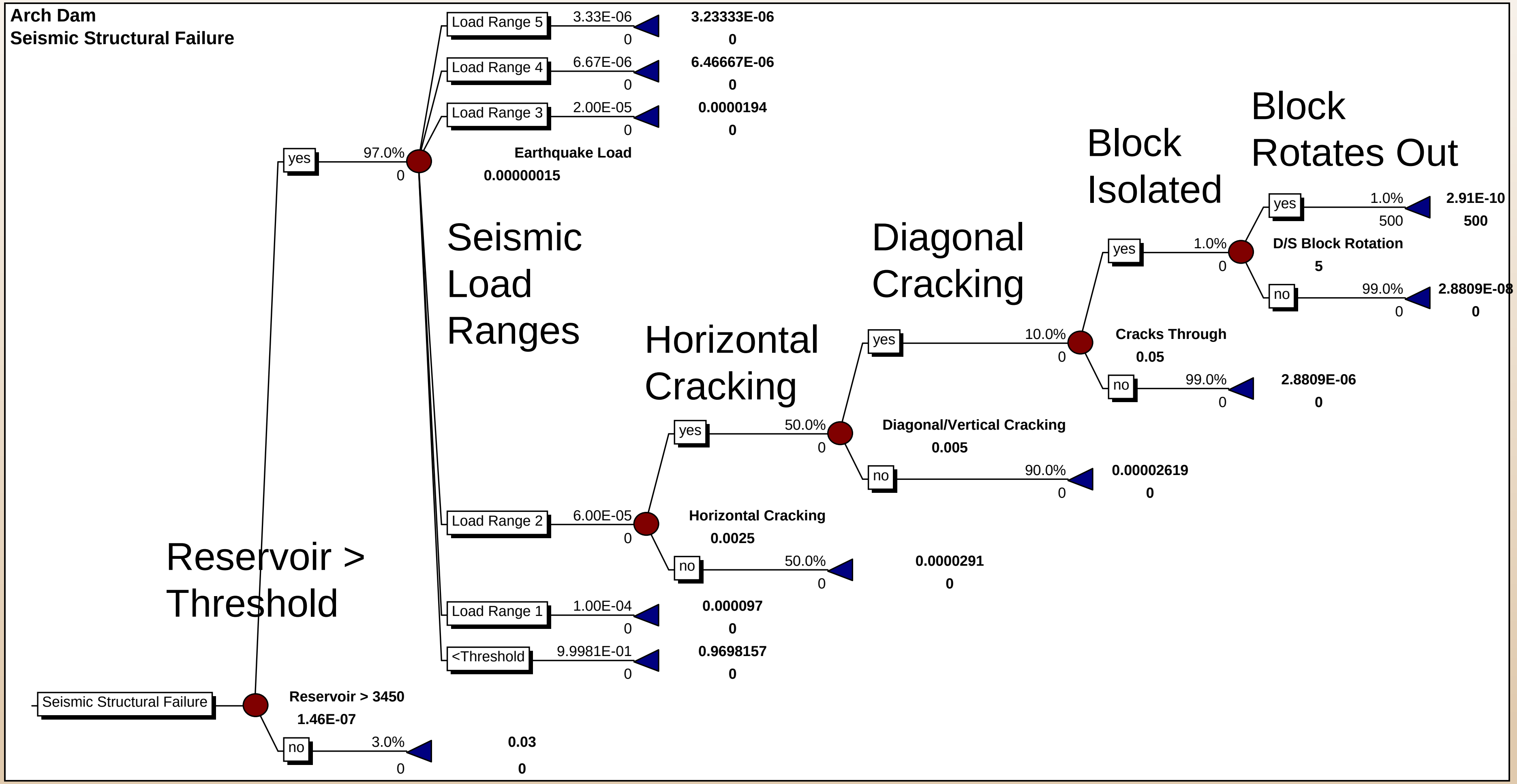
- Abutment erosion due to overtopping is a potential vulnerability (covered in another chapter)
- Adverse cracking could become critical under increased loading
- Generally, if arch structure handles static load, unlikely additional hydrostatic pressure from flood loading will increase structural risks when flood load probability is considered

# Seismic Loading

# Seismic Structural Failure

- No known arch dam failures during earthquakes
- Shake table model studies show structural failure mode
- Horizontal cracking near center
- Diagonal cracking parallel to abutments
- Rotation of isolated blocks

# Seismic Structural Failure




Note: Only one reservoir range is critical in this example. Analyses may indicate diagonal cracking occurs first (adjust event tree), Temperature ranges not evaluated.

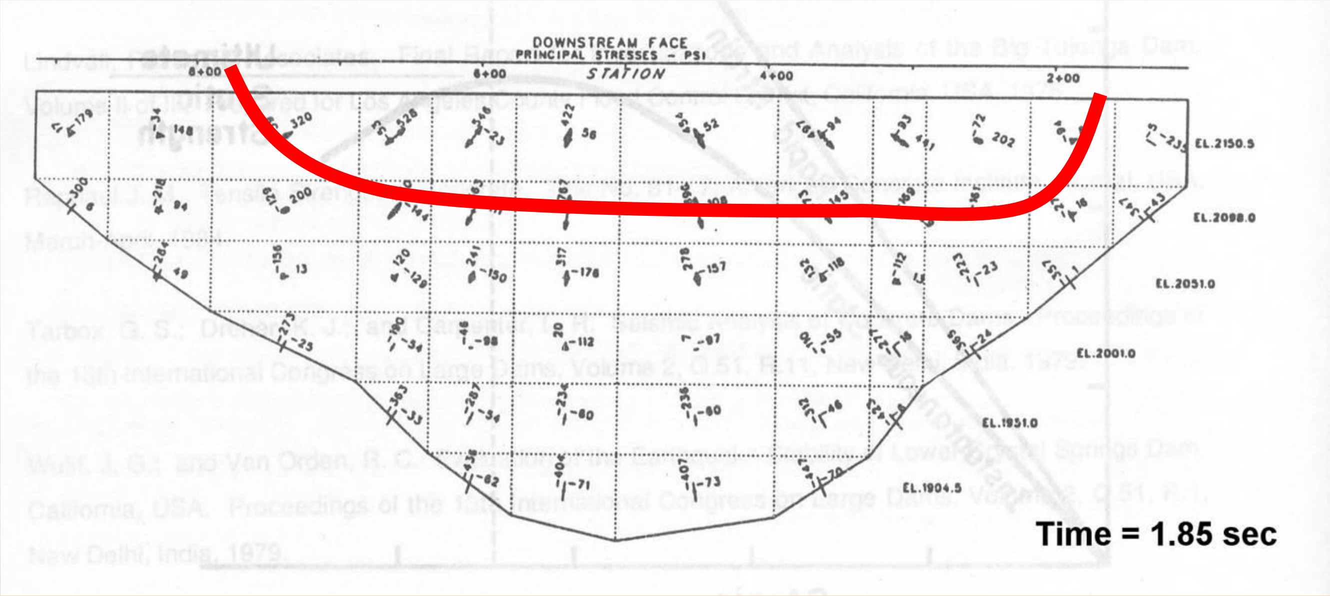
# Seismic Structural Failure

- 3-D time-history finite element analyses needed (consider variations in reservoir, temperature, and seismic load)
- Examine principal tensile stresses (vertical and diagonal) in relation to tensile strength (see section on concrete properties considerations)
- Evaluate potential location and orientation of cracking patterns
- Estimate the probability of kinematic displacement of any blocks isolated by cracking/ contraction joints (separate Newmark type analyses or nonlinear analysis may be useful)

# Analysis Progression

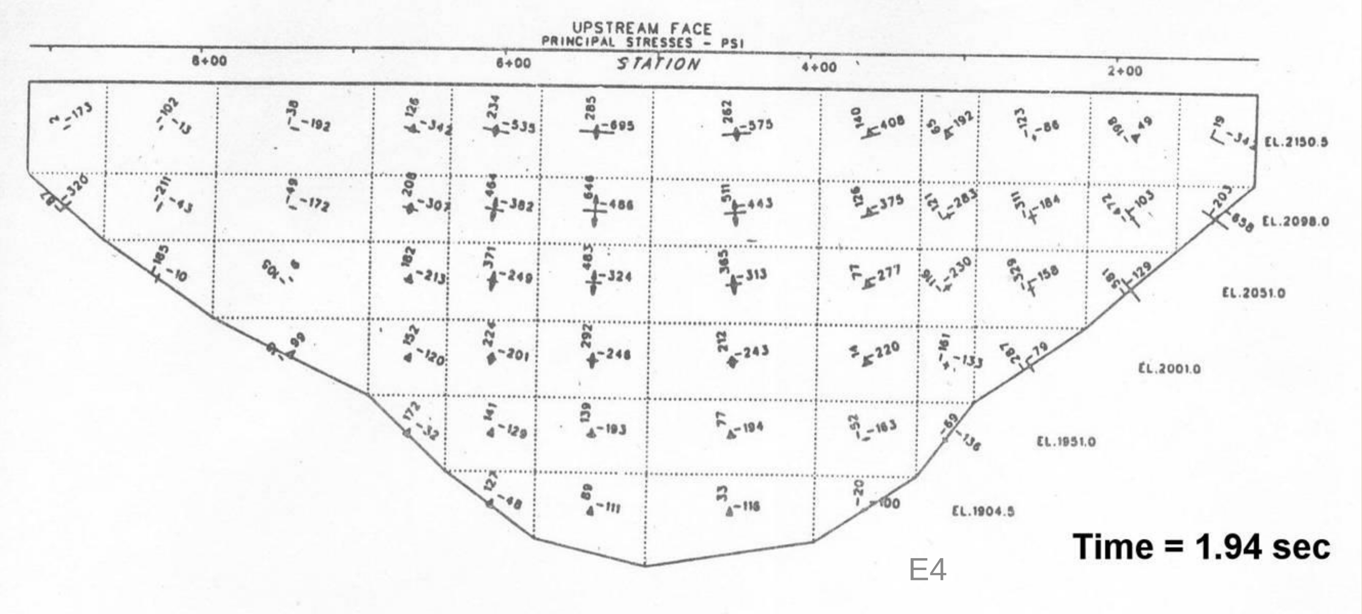
- Note: Although arch dams typically require a 3-D finite element analysis to draw any meaningful conclusions, initial analyses should be as simple as possible (for example, linear-elastic, massless foundation and added mass for hydrodynamic interaction) and progress to more sophisticated analyses as needed.

# Seismic Structural Failure



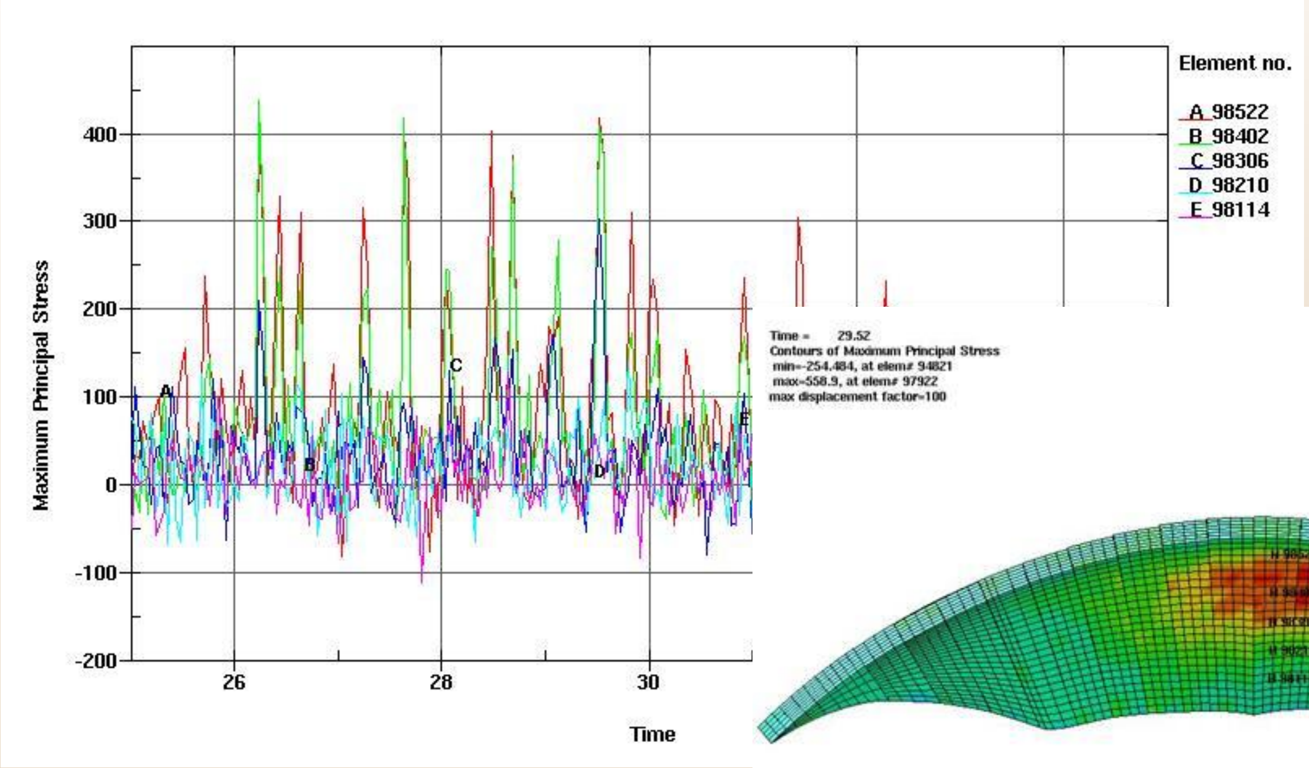

D/S face

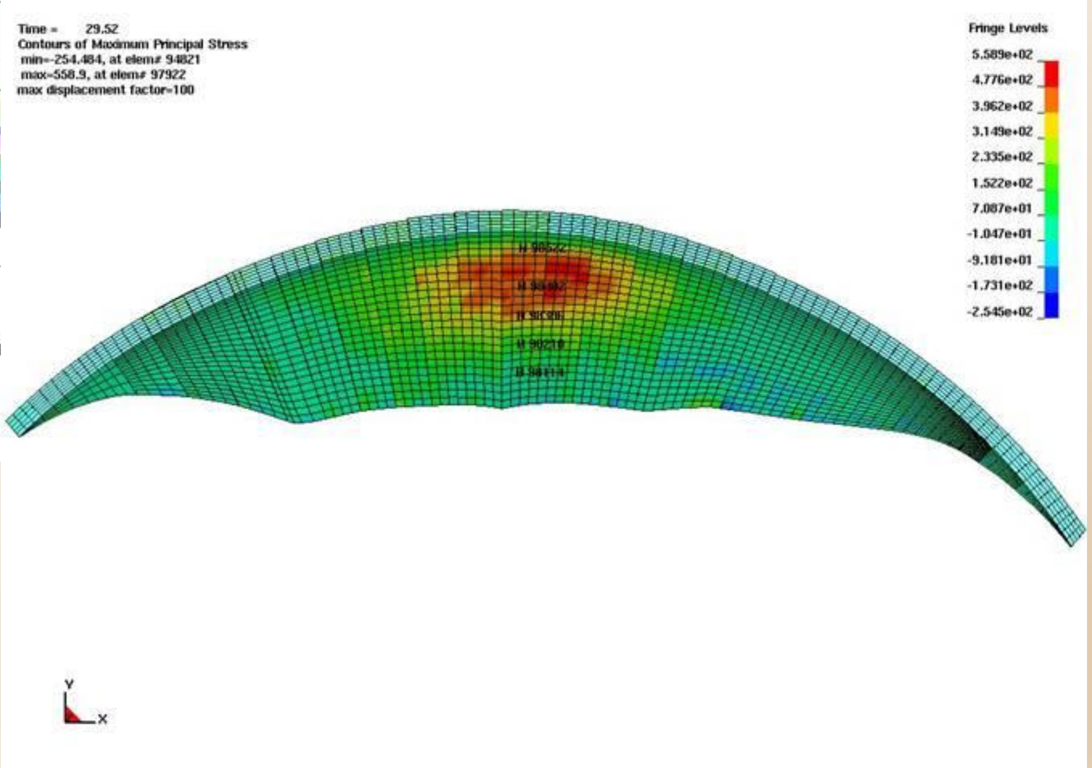
Results from analyses can be used to estimate failure modes such as those indicated by the physical model studies




U/S face

# Structural Failure




Principal stresses and associated histories from nonlinear analysis (contraction joints can open)

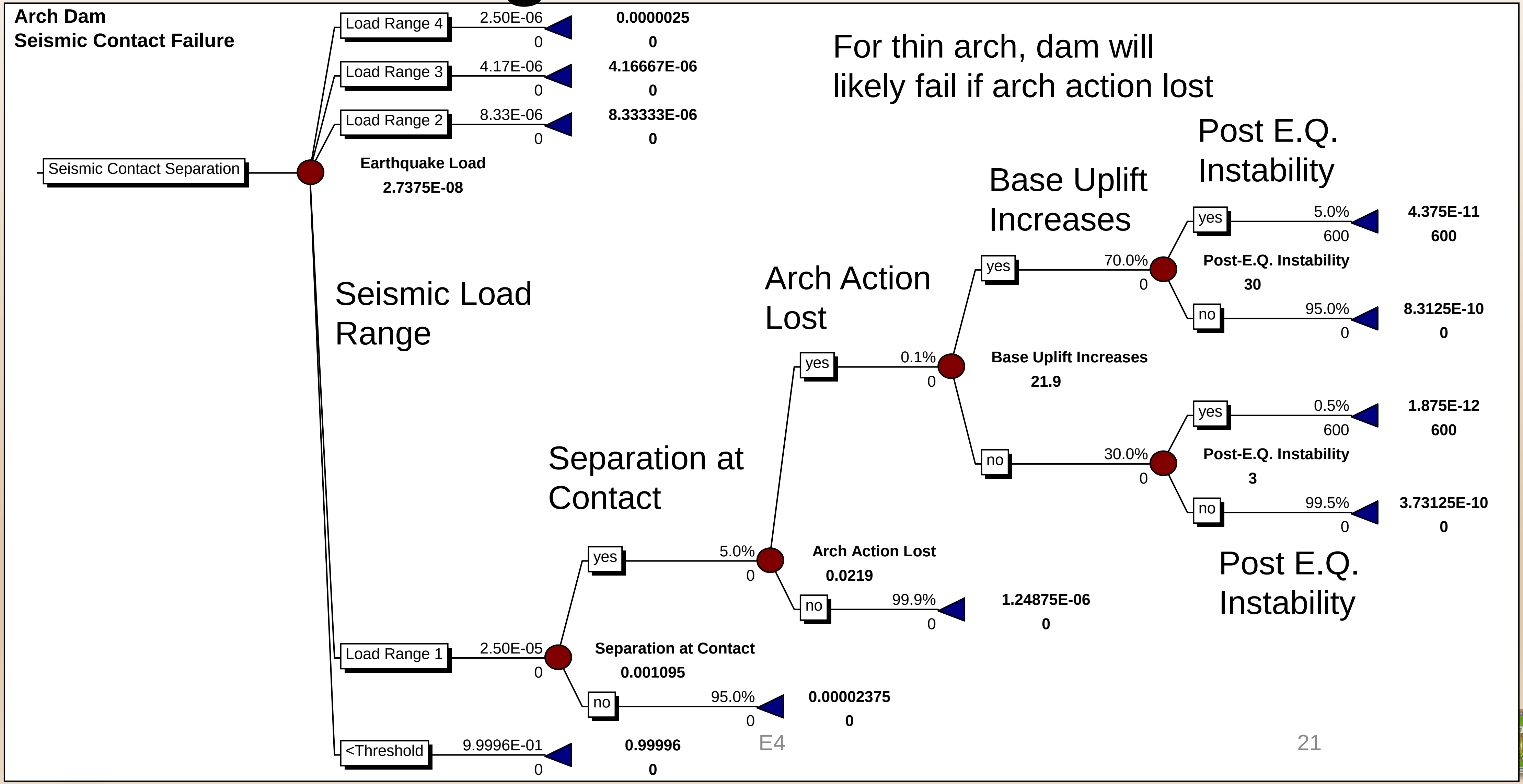
# Seismic Structural Failure

- If arch cracks all the way through:
  - How likely is it that the cracking pattern will be adverse enough to allow block displacement (i.e. semicircular cracking pattern smaller on u/s face than d/s face)?
  - How likely is it that the cracked condition would manifest early in the earthquake such that there would still be sufficient earthquake energy to displace and rotate the block?

# Contact Failure/ Sliding

- Typically only a concern for non-radial abutments that “open up” in downstream direction
- Under strong shaking, the contact can be broken and monoliths can slide at their base
- If upper blocks move, arch action can be lost
- Loss of arch action will likely result in failure of a thin arch
- A thick arch may be stable two-dimensionally

# Thick Arch Seismic Contact Failure/Sliding



# Contact Failure/Sliding

- Nonlinear analysis can be used to look at contact separation and subsequent sliding
- Otherwise base judgment on calculated stress levels (see section on concrete properties considerations)
- Enough displacement to lose arch action?
- Post e.q. stability could be important for thick dams


Nodes that separated for 50k earthquake at 5% damping

# Takeaway Points

- Arch dams are forgiving structures as long as the abutments can carry the transferred load. If an arch dam has performed well, the chance of structural failure under normal conditions or small increases in reservoir load is small.
- Although no arch dams are known to have failed during an earthquake, most risk-driver potential failure modes are related to seismic loading. Shake table model tests give insight for the potential failure progression.
- 3-D dynamic finite element analyses are typically needed to evaluate dynamic behavior and probability of failure.

# Questions or Comments?